MEGABAR LINER EXPERIMENTS ON PEGASUS II

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Abstract

Using pulsed power to implode a liner onto a target can produce high shock pressures for many interesting application experiments. With the Pegasus II facility in Los Alamos, a detailed theoretical analysis has indicated that the highest attainable pressure is around 2 Mbar for a best designed aluminum liner. Recently, an interesting composite liner design has been proposed which can boost the shock pressure performance by a factor 4 over the aluminum liner. This liner design was adopted in the first megabar (Megarbar-1) liner experiment carried out on Pegasus last year to verify the design concept and to compare the effect of Rayleigh-Taylor instabilities on liner integrity with the code simulations. We present briefly the physical explanation why the composite liner provides the best shock pressure performance. The theoretical modeling and performance of Megabar-1 liner are discussed. Also presented are the first experimental results and the liner design modification for our next experiment.

1. Introduction

Using pulsed power to implode a liner through z-pinch onto a target can produce high shock pressures for many interesting application experiments. Three years ago, a solid aluminum liner which could produce shock pressures in the hundreds of kbar regime was designed [1] and fielded [2] at the LANL Pegasus II facility. This liner design has since been used successfully for a variety of physics experiments. These results naturally generated considerable experimental interests to produce shock pressures in the megabar regime. Using the full bank voltage accessible to Pegasus II, a detailed theoretical analysis has indicated that the highest attainable pressure is around 2 Mbar (on a high-density target such as tungsten or platinum) if we optimize the liner made of aluminum, which can be shown to outperform other materials. Based on the general behavior of the collision shocks inferred from the Hugoniots and a general analysis of the Ohmic heating constraints on various liner materials, Lee has recently proposed a composite liner design [3] which can improve greatly the attainable shock pressure close to the physical limit. We refer the readers to Ref. 3 for the systematic physical analyses that led to this liner design concept. Due to space limitation, we will only discuss briefly in next section the pertinent physical reasoning to explain why the composite liner gives us the best pressure performance.

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14. ABSTRACT
Using pulsed power to implode a liner onto a target can produce high shock pressures for many interesting application experiments. With the Pegasus II facility in Los Alamos, a detailed theoretical analysis has indicated that the highest attainable pressure is around 2 Mbar for a best designed aluminum liner. Recently, an interesting composite liner design has been proposed which can boost the shock pressure performance by a factor 4 over the aluminum liner. This liner design was adopted in the first megabar (Megarbar- 1) liner experiment carried out on Pegasus last year to verify the design concept and to compare the effect of Rayleigh-Taylor instabilities on liner integrity with the code simulations. We present briefly the physical explanation why the composite liner provides the best shock pressure performance. The theoretical modeling and performance of Megabar- 1 liner are discussed. Also presented are the first experimental results and the liner design modification for our next experiment.

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Subjecting the liner to more Ohmic heating will increase the collision velocity, the limit is set by the requirement that the integrity of its inner surface should not be perturbed by the Rayleigh-Taylor instabilities. The Megabar-1 experiment was carried out last year to certify the basic design and to benchmark experimentally the limit given by our code simulations. The optimized parameters, designed performance, and experimental setup for Megabar-1 liner are presented in Section 3, followed by the discussion of 1-D code simulation results on the liner performance. The 2-D modeling of the liner implosion and experimental results are given in Section 4.

2. General Results on Composite Liner Design

The peak shock pressure generated from the liner-target collision depends on the collision velocity v_c and the material properties. In the multi-megabar regime, the Hugoniot for a material (labeled by k) can be adequately represented in the form as

$$P_k(v) = \rho_k v(c_k + s_k v),\qquad\qquad(1)$$

where v is the particle velocity measured in the rest frame of the material before impact, ρ stands for density, and c and s are constants depending on the material. When two materials a and b collide at a velocity v_c, the resulting shock pressure, $P_{ab}(v_c)$, is given by the intersection of $P_a(v)$ and $P_b(v_c-v)$ in the P-v plane. Although one can obtain the analytic solution for $P_{ab}(v_c)$ exactly, the long expression is not illuminating for useful insight. However, it has been found empirically that, for a wide variety of materials [4], c is around a few mm/μs and $1.2 < s < 2$. Based on this observation, Lee has derived [3] an approximate expression generally valid in the megabar regime as

$$P_{ab}(v_c) \approx \frac{v_c^2}{[(s_a\rho_a)^{-1/2} + (s_b\rho_b)^{-1/2}]^2}.\qquad\qquad(2)$$

From Eq. (2) we see that $P_{ab}(v_c)$ increases with v_c quadratically, and also with ρ_a and ρ_b quasi-linearly.

But because the Ohmic heating limit discussed earlier, the highest collision velocity attainable depends sensitively on the following liner material properties: electric conductivity, density, melting point, and specific heat. This constraint implies that the collision velocity and density cannot be varied independently. In fact one can deduce the conclusion [3] that, aided by the electrical action data compiled [5] for various metals, the aluminum gives the highest liner velocity before melt, mainly due to its high electric conductivity and low density. Furthermore, the aluminum liner enjoys such a big velocity advantage (three times higher than the next best, copper) that it will also outperform others in shock pressure, on any target, in spite of its low density. Even so, the highest pressure we can achieve is just around 2 Mbar for the best designed aluminum liner using the maximum driving current at Pegasus.

The composite liner design can maximize the numerator and minimize the denominator of Eq. (2) almost independently and thereby enables us to approach the physical limit of pressure performance. Imagine that we have an aluminum liner already optimized in v_c for a given driving current, now let us add a high-density material such as platinum on the

inside by a small mass fraction. Clearly, the platinum will not reduce the optimized v_c significantly for this composite liner, but it enhances greatly the density of the impact layer. Using the empirical [4] values $s_{Al} = 1.34$ and $s_{Pt} = 1.54$, we find from Eq. (2) that such a composite liner outperforms the aluminum one in shock pressure by 4 (2.3) times on a platinum (aluminum) target. In some application, the experimental requirement on the peak shock duration may force us to increase the platinum mass at the expense of lowering the collision velocity.

3. Designed Performance and Experimental Setup for Megabar-1 Liner

As we implode the liner with a high current, the outer layer of the liner will melt first due to the fact that the current diffuses from outside in. Consequently, the Rayleigh-Taylor instabilities will develop in the liquid layer. In order to achieve the expected shock pressure experimentally, the inner liner surface must remain smooth, cylindrical, and concentric to the target. Concentric implosion can be achieved if the diagnostic windows cut out in the return conductor are arranged in an n-fold rotationally symmetric configuration. The megabar-1 liner was intentionally designed to push the Ohmic heating near its upper limit as given by our 2-D magneto-hydrodynamic (MHD) code simulations. But we need experimental verification to benchmark the simulations as the latter depends on the accuracy of the conductivity table, strength model, and equation-of-state (EOS) database.

The Megabar-1 liner consisted of 8 g of 1100 series aluminum, and 1 g of platinum plated on the inside; it was 2 cm long and .77 mm thick and had an inner radius of 3 cm. These parameters are obtained from 1-D code simulations by optimizing the liner velocity at
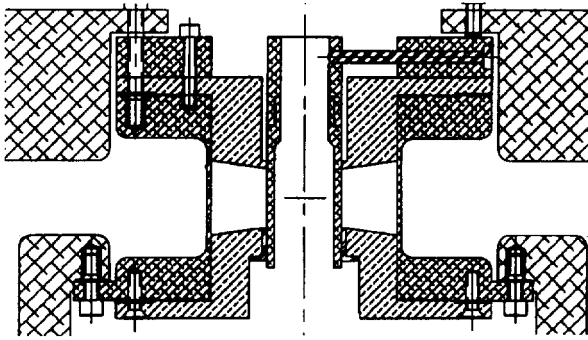
Fig. 1. Schematic diagram to show Megabar-1 experimental configuration of the liner, pin cylinder, and glide-planes.
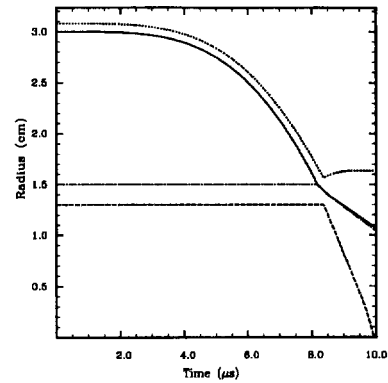
Fig. 2. Inner and outer radii of Megabar-1 liner versus time.

target radius of 1 cm, using the full bank voltage for Pegasus at 90 kV, under the condition that the inner aluminum surface reaches its melting point at the radius 1.5 cm. The drive current was approximately sinusoidal with a peak of 12.2 MA at 7.5 μs. Performance of the machine was diagnosed with Faraday rotation fibers, a Rowgowski loop, and B-dot probes. Two Conical-shape copper electrodes known as glide planes were cut at an angle of 8^0 with respect to the mid-plane, as shown schematically in Fig. 1, to keep the liner in good contact during implosion. The angle was determined from the 2-D simulation that gave the best overall cylindrical shape to the inner liner surface.

The 1-D MHD code simulation indicates that the liner velocity can reach 7.9 mm/μs at a target radius of 1 cm and generate a shock pressure of 8 Mbar on a platinum target. The peak shock lasts only 6 ns, which is limited by the thickness (about 37 μm) of the platinum layer at collision time. In Fig. 2 we display the liner motion versus time. The platinum layer is too thin to be resolved in the plot, so it merges with the inner aluminum surface as one curve. Notice that in this experiment we have installed a pin cylinder with an outer radius of 1.5 cm to measure the liner velocity. The 1-D simulation indicates that the aluminum layer starts to melt from the outer surface at 4 μs and melts completely at 7.5 μs; but the platinum layer remains solid even at 1 cm, the intended target radius.

4. 2-D Modeling of Liner Implosion

An axial-symmetric, 2-D Eulerian MHD code has been used to model the liner and the electrode glide-planes. Because of zoning restrictions, the inner platinum layer has not been included in these 2-D simulations, but has been replaced with aluminum of equal mass so that the equation of motion remains the same. The calculations include an elastic-plastic strength model and melt model. The plastic regime includes the Steinberg-Guinan model for work hardening, as well as temperature and density dependent strength parameters.

The 2-D simulations examine several aspects of liner performance, including: the initial liner motion, the quality of the liner-electrode contact during implosion, the effect of perturbations from the liner ends and subsequent instability growth as the liner implodes, and the integrity of the liner's inner surface at the target radius. The last is particularly important if the liner is to be used in applications experiments, where a sharp liner-target impact is essential. In our simulations the liner is initially perfectly smooth, ignoring any non-uniformity associated with surface finish (less than 0.4 μm). Despite their absence in the initial model, calculations indicate that perturbations are initiated from both ends as the liner move along the electrodes, and propagate axially inward with time. Using a representative sound speed around 3 mm/μs, the axial transit time for the stress disturbances along the liner is about 7 μs. Therefore, the disturbances from the two ends will overlap and interact along the entire liner before the collision. Calculations with all conditions fixed except the glide-plane angle, which was varied from 4 to 12 degrees in increment of 2°, shows that the wave length and amplitude of the induced perturbations are sensitive to angle, and do not vary in a simple manner.
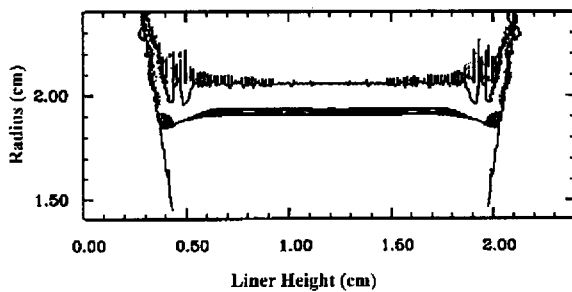

Fig. 3. Contour plot of the radial stress-deviators in the r-z plane from 2-D modeling at liner radius 1.9 cm.
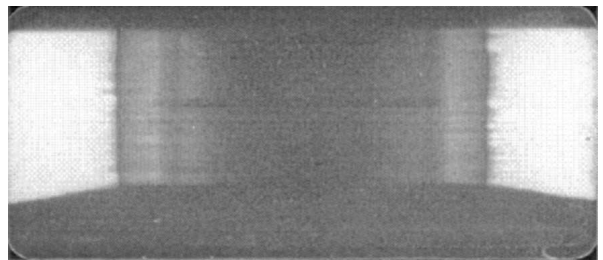
Fig. 4. X-ray radiograph of Megabar-1 liner taken at radius 1.9 cm.

Figure 3 shows contours of the radial stress-deviators in the r-z plane when the liner reaches a radius of 1.9 cm at $t = 7.34$ μs. According to the simulation, most of the liner has melted at this point except a thin (about 0.2 mm) inner portion. Near the electrodes, however, the liner has melted completely over an axial extent of about 0.1 mm. The instabilities associated with electrode-induced perturbations are worst within a few mm of each glide-planes, but have not produced any significant deformation in the remaining solid layer. The radiographic data at the same radius, as shown in Fig. 4, indicate that there is more spike-shape structures with larger amplitudes on the outer liner layer than the simulation. Because the line-of-sight is not perpendicular to the liner axis, the top electrode in Fig. 4 does not show the cone angle as the bottom one.

As we scan the densitometry readings of the radiographic film along the radial direction for various axial positions, the sharp minimum in each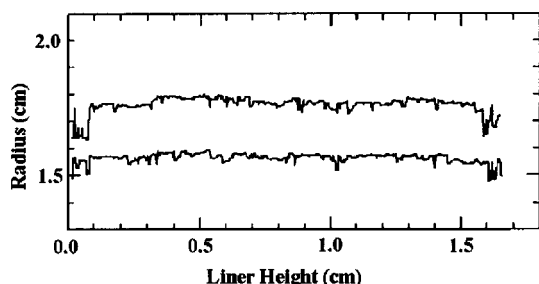 scan gives the location of the inner liner surface. Two profiles of the inner surface so determined are shown in Fig. 5, with a standard deviation of 0.14 (0.12) mm in radius for the top (bottom) one. For visual clarity, we displace the bottom profile by 2 mm. Notice that both ends of each profile are ahead of the bulk of the liner by about 1 mm, as predicted by the simulation displayed in Fig. 3.

Fig. 5. Profiles of inner liner surface reduced from the radiographic data. For clarity we displace the bottom profile 2 mm lower.

As mentioned earlier, the Megabar-1 liner was intentionally designed to stress the system in order to determine the Ohmic heating limit for maintaining the liner integrity. Our experimental data suggest that the instabilities in the actual liner are certainly worse than our modeling, which neglects the tiny surface finish non-uniformity. Accordingly, we have modified the liner design more conservatively for our next experiment (Megabar-2). The Megabar-2 liner consists of 9 g aluminum and 1 g platinum, and has an inner radius 2.5 cm. According to our 1-D simulation, the liner can reach a collision velocity of 7.0 mm/μs, on a platinum target at 1 cm, and generate 6.3 Mbar in shock pressure. The larger mass and smaller radius give us a 30% thicker aluminum layer compared to the Megabar-1 liner. Modeling of this new liner (again with 10 g all aluminum) has been carried out in the same manner.

The left and right halves of Fig. 6 are the contours of radial stress-deviator in the r-z plane, corresponding to the 8° and 6° glide-plane angle, respectively, when the liner reaches 1.7 cm at $t = 6.64$ μs. The 6° model is preferred since the spectrum of instabilities in the liquid

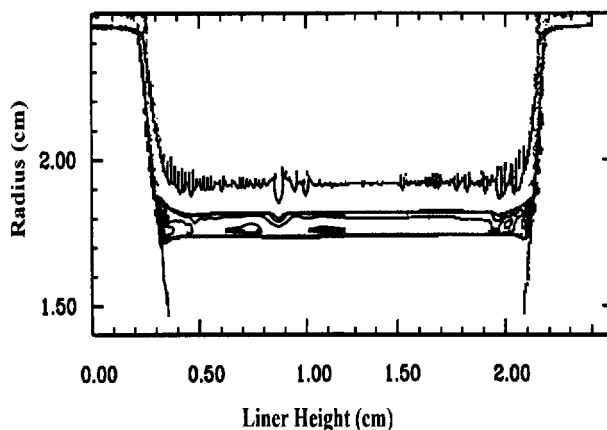Fig. 6. Contours of radial stress-deviators for liner at t = 6.64 μs. The glide plane angle for the (left) right half is 8° (6°).

layer consists of smaller amplitude and wavelength features. Finally, Fig. 7 shows the 6 degree model at t = 7.59 μs, only 2 mm away from the target radius. The inner liner surface exhibits a small but noticeable bowing along the axial direction. The result suggests that a further reduction in the glide-plane angle may help. An alternative is to make the glide plane angle varying with the radius.

Fig. 7. Contours of radial stress-deviators for Megabar-2 liner at t = 7.59 μs.

The 2-D models indicate that the liner-electrode stress perturbations and their interactions with the magnetically driven Rayleigh-Taylor instabilities are important issues for composite liner design to achieve multi-megabar pressures. Also important is to find out what is the surface finish tolerance that will not seriously affect the liner integrity through growth of instabilities. These physical issues are currently under study.
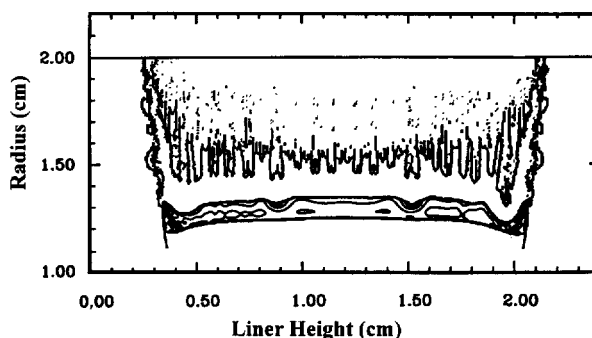
5. Conclusions

Megabar-1 experiment was carried out to verify the basic design of the composite liner proposed recently to maximize the shock pressure performance, and to benchmark our computational predictions on the integrity of inner liner surface. Radiographic data indicate that the effects due to Rayleigh-Taylor instabilities on the liner surface integrity is worse than our idealized code modeling, which neglects the surface finish non-uniformity. We have modified the liner design accordingly for our next experiment to be fielded this coming fall.

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